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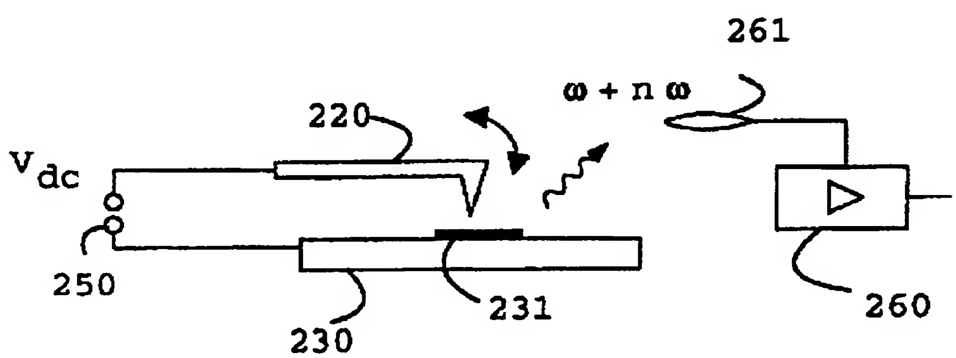

(57) Abstract

A new method and an apparatus for measuring the deflection of or the force exerted upon a cantilever-type micromechanical element is presented which is based on detecting radiation emitted from the gap between the cantilever (220) and a second surface (230, 231). The radiation, while occurring spontaneously at high frequencies when appropriately biasing the cantilever and the second surface by a voltage, can be enlarged by using external energy sources. The new method and apparatus are also applied to surface investigation, particularly to dopant profiling.

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DESCRIPTION

Cantilever deflection sensor and use thereof

This invention relates generally to to means for measuring the forces and/or deflections of cantilever type elements, as encountered for example in the field of Atomic Force Microscopy (AFM). The invention further relates to a method and apparatus for determining material properties. In particular, it relates to a dopant profiler based on a scanning probe microscope involving the generation and detection of higher harmonics of an applied electromagnetic field.

BACKGROUND OF THE INVENTION

The Atomic Force Microscope as first known from the United States patent US-A-4 724 318 and further described by G. Binnig, C.F. Quate and Ch. Gerber in Phys. Rev. Letters, Vol.56, No.9, March 1986, pp.930-933, employs a sharply pointed tip attached to a spring-like cantilever beam to scan the profile of a surface to be investigated. At the distances involved, minute forces occur between the atoms at the apex of the tip and those at the surface, resulting in a tiny deflection of the cantilever. In US-A-4 724 318, this deflection is measured by means of a tunneling microscope, i.e., an electrically conductive tunnel tip is placed within tunneling distance from the back of the cantilever beam made also conductive, and the variations of the tunneling current are used to determine the deflection. With known characteristics of the cantilever beam, the forces occurring between the AFM tip and the surface under investigation can be determined.

The forces occurring between a pointed tip and a surface are usually described as van-der-Waals, covalent, ionic, or repulsive core interaction forces.

An important aspect of AFM is to accurately determine the deflection of the cantilever. One group of these defection measuring methods is based on coupling the cantilever to another distance sensitive microscope. A combination of the cantilever with a scanning tunneling microscope is described, for example, in the above mentioned patent US-A-4 724 318. Another approach using an evanescent wave coupling sensor, also known as scanning near-field optical microscope (SNOM) or scanning tunneling optical microscope (STOM), is described by Diaspro and Aguilar in: Ultramicroscopy 42-44 (1992), pp. 1668-1670.

Another group of detecting methods is based on the well known piezoelectric or piezoresistive effect. An example is described in: M. Tortonese et al., Appl. Phys. Lett. 62(8), 1993, pp.834-836. These methods provide detection schemes in which the deflection detector is integrated in the cantilever.

Yet another feasible way of detecting the displacement of the cantilever relies on capacitance sensing and is known, for example, from Joyce et al., Rev. Sci. Instr. 62(1991), p. 710, and Göddenhenrich et al., J. Vac. Sci. Technol. A8(1990), p. 383. and the European patent application EP-A-0 290 648.

By this application as well as from United States patent US-A-4 851 671 methods are known use the changes in the resonance frequencies of the flexible element and higher harmonics thereof to measure its bending. The frequencies are detected either by a quartz oscillator or by a capacitance additionally attached to the cantilever.

The displacement of the flexible element can also be measured by applying optical methods, such as beam deflection or interferometry. The beam deflection method makes use of the length of the lever. Usually, a light beam, preferably produced by a laser diode or guided through an optical fiber, is directed onto the lever. A small deflection of the lever causes a reasonable change in the reflecting angle and, therefore, results in a deflection of the reflected light beam that is measured with bicell or other suitable photo detectors. The beam deflection method is simple and reliable. It is described, for example, by Myer and Amer in Appl. Phys. Lett. 53 (1988), pp.1045-1047. Interferometric methods are described, for example, by Martin et al., J. Appl. Phys. 61(1987), p.4723, by Sarid et al., Opt.Lett. 12(1988), p.1057, and by Oshio et al., Ultramicroscopy 42-44(1992), pp.310-314. As the sensitivity of the SPM can be increased by building cantilevers with ever higher resonance frequencies while trying to maintain the Q factor, a tendency towards smaller cantilevers can be observed. For these cantilevers the above optical methods are prone to failure due to a diminished reflectivity and problems which arise from the limited focus size of a laser beam.

Present day very large scale integrated (VLSI) circuit technology demands an accurate knowledge of the spatial extent, density, or distribution in all three dimensions of the active components (dopants) which are introduced into a base or host material. The most common devices produced by VLSI are either bipolar or metal oxide semiconductor field effect (MOSFET) transistors, diodes or capacitors. The characteristic length scale - at present at about 0.5 microns - will shrink in the future to 350 nm and even to 100 nm. The concentration of dopants, for example arsenic, boron, or phosphorous, in an active region of a semiconducting device ranges typically from $10^{15}/cm^3$ to $10^{20}/cm^3$. It will become necessary to control the variation, or profile, of dopants with a lateral resolution of 10 nm and a vertical resolution of 2 - 3 nm to accomplish predictability in device behavior and control of the manufacturing process. However, currently known dopant

profilers are unable to provide this high precision, at least in all three dimensions.

Known approaches to dopant profiling include junction staining as described by S.T. Ahn and W.A. Tiller in the J. Electrochem. Soc. 135 (1988), p. 2370, dopant density selective etching with Transmission Electron microscopy (TEM) as described in the J. Vac. Sci. Technol. B 10 (1992), p. 491, by H. Cerva, Secondary-Ion Mass Spectroscopy (SIMS), Spreading Resistance (SR), and macroscopic Capacitance-Voltage (C-V) measurement, all described for example in S.M. Sze, "VLSI Technology", McGraw-Hill Book Co., New York, 1983 (in particular chapters 5 and 10). Other methods, currently under development are dopant density selective etching with a Scanning Tunneling Microscope (STM), which is known from L.P. Sadwick et al., J. Vac. Sci. Technol. B 10 (1992), p. 468, planar STM, described by H.E. Hessel et al. in J. Vac. Sci. Technol. B 9 (1991), p. 690, and cross-sectional STM, described by J.M. Halbout and M.B. Johnson in J. Vac. Sci. Technol. B 10 (1992), p. 508. Though being in some aspects useful, these techniques suffer from several drawbacks: they are either destructive or require a careful sample preparation, or have a limited lateral resolution or sensitivity to dopants.

One of the most recent methods to determine the dopant concentration is the Scanning Capacitance Microscope described in the United States patent US-A-5 065 103. It shows features of the scanning probe microscopy and of the conventional C-V technique. But even the Scanning Capacitance Microscope lacks a sufficient lateral resolution as will be required in the future. Further, it employs a lock-in technique to reduce the noise due to stray capacitance thus slowing down the scan process and makes a high throughput by this method improbable.

Another method, described in US-A-5 267 471, employs a cantilever with two different mechanical resonant frequencies. When using this device as a capacitance sensor, fractions of the resonant frequencies are applied to the

cantilever, and its movement is monitored by a laser interferometer and a subsequent lock-in amplifier. As above, the use of a lock-in amplifier severely restricts the bandwidth of the measurement.

The principles of scanning probe microscopies based on field-induced higher harmonic generations (SHM) are described for example by G.P. Kochanski in Phys. Rev. Lett. 62 (1989), No. 19, pp. 2285-2288, by W. Seifert et al. in Ultramicroscopy 42-44 (1992), pp. 379-387, by B. Michel et al. in Rev. Sci. Instrum. 63 (9), Sept. 1992, pp. 4080-4085, and by S.J. Stranick and P.S. Weiss in Rev. Sci. Instrum. 64 (5), May 1993, pp. 1232-1234. In SHM techniques an electromagnetic field of Radio (rf) to optical frequencies, is applied to the tunneling gap of a conventional scanning tunneling microscope (STM). Due to some electric properties of the tunneling gap, which are believed to be either non-linearities of the current-voltage curve or space-charge effects, higher frequencies (harmonics) are generated. Using these higher harmonics as feedback for the STM tip positioner, isolating films and semiconductors can be scanned. However, the feedback loop fails over a conducting surface, leading to a crash of the fragile tip on the surface. This fallacy prevents the large scale use of the SHM as an instrument for dopant profiling, as conducting areas are regularly encountered on an integrated circuit.

With regards to the described limitations of the art, it is therefore an object of the invention to provide an apparatus for determining the deflection of a cantilever which is particular suitable for cantilevers with small dimensions and hence very high resonance frequencies. A further object of the invention is a non-destructive method and apparatus to determine characteristic properties of a material, in particular the dopant profile, with a resolution expansible below 100 nm. The method and apparatus should be equally applicable to conductive and non-conductive surfaces. It is another object of the invention to increase the bandwidth of the deflection measurement with regard to the known devices.

SUMMARY OF THE INVENTION

The above-mentioned and other objects and advantages are attained in accordance with the principles of the present invention as set forth in the appended claims.

Accordingly, in a basic variant the apparatus in accordance with the invention comprises a flexible cantilever, voltage biasing means to apply a DC voltage between the cantilever and either a sample to be investigated during operation of the apparatus or a "piggybacked" reference surface or tip, antenna means to receive radiation in the MHz and/or GHz range, and amplifying means designed to operate in this range. Due to non-linearities of either the resistance-to-voltage or capacitance-to-voltage characteristic of the interface between the cantilever and the second surface, the radiation emitted from the interface area has not only one (fundamental) frequency, but simultaneously contains components with higher frequencies, the so-called harmonic signals. Though in principle all these components can be used, it is found that in some embodiments of the invention advantageously harmonic signals, in particular the second and third harmonic signals, are exploited for measurements, as will be further described below. The preferred range of frequencies is 100 MHz to 100 GHz, whereby the lower limits is set by the efficiency of the higher harmonic generation and the upper limits reflects the currently available equipment for the generation and detection of high frequency signals.

The generation of higher harmonics requires usually that the cantilever and the second surface, which can either be the surface of a sample or of a "piggybacked" plane or tip, form an interface consisting of a semi- or non-conductive boundary and a conductive boundary. However, it is found that the sensitivity of a device in accordance with the invention supports an embodiment in which both surfaces are made of semiconducting materials.

Thus, the device shows a high efficiency in the generation of higher harmonic signals, irrespective of the nature of the second boundary. As another advantage of the invention, a constant DC bias voltage can be chosen without the need of a re-adjustment when for example during a scan of the cantilever different surface materials are encountered.

The two boundaries are separated by preferably 0.1 nm to 100 nm. Using the voltage biasing means, a DC voltage can be applied to this interface. The oscillations of the cantilever then cause the emission of an electrical field signal oscillating with the resonance frequency and with higher harmonics, thereof, due to the non-linear capacitance-to-voltage characteristic of the interface. The emitted electrical field is detected by the antenna and the amplifier or the cascade of amplifiers and filters, preferably forming a spectrum analyzer. Variations of the force acting upon the tip of the cantilever, and hence the deflection of the cantilever can be detected as shifts in the frequency of the electrical field signal or in the amplitude of the cantilever's oscillation.

The basic variant of the invention can be augmented to a deflection detection and control apparatus by applying the output signal of the amplifier to feedback means which control positioning means, e.g., piezoelectric fine positioning systems, known as such in the art, allowing in combination a control of the position of the cantilever with atomic precision. This embodiment of the invention especially suitable for cantilevers with a resonance frequency of several hundred MHz or higher. These cantilevers are too small to apply known optical methods, such as beam deflection or interferometry, as the light can no longer be properly focussed and the amount of light reflected by the cantilever falls below current detection thresholds.

As described with respect to the patent US-A-4 724 318, it is in principle known to use a "piggybacked" Scanning Tunneling Microscope (STM) to detect the deflection of a AFM cantilever. It will however become clear that

the differences with respect to this invention result in several advantages. Tunneling current detection requires the tip to approach the back of lever up to less than one nm. This close distance causes a strong damping and is impractical when measuring large forces and force gradients, i.e., large deflections. Another reason which prevented the use of this method in commercially available AFM microscopes is the lack of stability of the tunneling gap under ambient conditions. With an apparatus in accordance with the invention, the gap width can be enlarged up to 50 nm. The damping of the silicon cantilever is much smaller, while the sensitivity for measuring deflection can be maintained at a very high level. In addition, the new apparatus does not suffer from the stability problems characteristic for an AFM with tunneling current detection of the deflection. It even can be performed on surfaces that are covered with an insulating, e.g, oxide or nitride, layer

Embodiments of the invention can easily be applied to any type of existing cantilever without the need of an accurate adjustment or alteration of the cantilever itself. A device according to the invention is found to have a good signal-to-noise ratio and therefore does not require a lock-in amplifier, thereby increasing the bandwidth of the deflection measurement.

Obviously, the scope of the invention is not restricted to simple beam-shaped cantilevers with a single support. It can readily be applied to more complex designs of cantilevers, having for example two or more support points, a spiral-like shape, etc.

Further embodiments of the invention concern the antenna which receives the electrical field emitted from the interface region: The antenna can either be a distinct conductive element or an integral part of the cantilever, of the sample carrier, or of the piggybacked element. In latter cases, means for separating the bias voltage and other low frequency components from the high frequency signal are provided, such as "bias tee" connectors. The antenna can also be integrated into a cavity, preferably into a tunable cavity,

as described for example by B. Michel et al. in Rev. Sci. Instrum. 63 (9), Sept. 1992, pp. 4080-4085. The use of a cavity allows the detection of a large percentage of the signal power provided that the cavity is tuned to the frequency of the signal. Without a cavity, a higher flexibility in measuring and instrument design is gained. The, however, reduced sensitivity may in this case be compensated by using specially designed high impedance filters and amplifiers.

A specific aspect of the invention is use of a device comprising a flexible cantilever and means for detecting higher harmonic electrical signals as described above for investigating heterogeneous surfaces, in particular for probing highly integrated circuits, i.e., dopant profiling.

It is known that the electrical signal emitted from the gap between tip and sample depends on the materials of which the boundaries of the interface are made of. However, the introduction of applicable dopant profilers failed so far as no known instrument has been versatile enough to cope with a complex surface as encountered in ICs. Though the scanning capacitance microscope is in principle able to scan across any surface, it has been impossible to maintain a high resolution under such arbitrary surface conditions. The invention solves this problem by using a device operable in an atomic force mode, in which the deflection of the cantilever is detected by any of the methods described above, and simultaneously enabling the detection of the electrical signal as emitted from the gap area.

Another embodiment further comprises means for generating an oscillating electrical field and coupling means to apply this field to the cantilever. In this embodiment, the frequency with which the gap between the tip of the cantilever and the surface of a sample is modulated is not determined by the resonance frequency of the cantilever but can be tuned to a predetermined value. This value may depend on the surface structure and composition of the sample to be investigated. Preferably a radio frequency or microwave frequency field is used. This embodiment is further improved

by providing appropriate filter means to separate the fundamental frequency signal, which is obscured by the externally supplied signal, from its higher harmonics.

In a variant of this embodiment, the externally supplied oscillating electrical field is utilized to control amplitude and oscillation frequency of the cantilever. This control is especially efficient when tuning the externally supplied field to the resonance frequency of the cantilever. Similar effect can be achieved when the cantilever oscillation is driven by a piezoelectric or piezoresistive elements forming part of the cantilever body with said elements being excited by externally provided electrical signals. Another alternative to excite oscillation is by providing a sufficient amount of thermal energy to the cantilever, which in this case should have a bimorph structure including material with different thermal expansion coefficients. The heat supply to the cantilever can be enhanced by including suitable heating elements into the cantilever structure.

sp In another embodiment of the invention, the tip is attached to means for measuring the current flowing through the gap between the tip and the surface. Thus, either the (DC) tunnel current as known from the conventional STM can be determined or an AC current arising from a small number of electrons which tunnel onto and from the surface to be studied under the influence of the applied AC electromagnetic field as described by Kochanski. In the latter case also applies to an insulator.

Both currents can be used as input signal to the feedback loop of the positioning device, giving the operator of an apparatus according to this invention two to four different methods of controlling the gap width between tip and sample.

In a particular preferred embodiment of the invention, the tip and the cantilever of the force sensor are combined to an atomic force cantilever with a conductive cladding or coating. This cladding can be applied to a normal AFM cantilever by any suitable deposition technique well known in

the art. This integrated tip structure reduces significantly the technical overhead as compared to a device in which a atomic force sensor has to be applied in parallel to the (metallic) tip of conventional scanning harmonic microscopes (SHMs).

It is immediately possible to apply the signal detection to an array of cantilevers, each tuned for example to a slightly different resonance frequency. The deflection of each cantilever can be accomplished by either coupling the input DC voltage or the input electromagnetic wave selectively to each one of these cantilevers or by tuning a frequency detection device to its resonance frequency.

The efficiency of the apparatus can be further enhanced by employing an enclosing chamber and means for controlling the humidity in the interface region as described for example by J.-P. Bourgoin et al. (International Conference on Micro- and Nano-Engineering MNE '94, Davos, Switzerland, Sept. 26-29, 1994) in case of a known scanning surface harmonic microscope. The humidity when set to an appropriate value gives rise to the formation of a tiny droplet in the interface region and thus concentrates the electrical field in this region.

These and other novel features believed characteristic of the invention are set forth in the appended claims. The invention itself however, as well a preferred mode of use, and further objects and advantages thereof, will best be understood by reference to the following detailed description of illustrative embodiments when read in conjunction with the accompanying drawings.

DESCRIPTION OF THE DRAWINGS

The invention is described in detail below with reference to the following drawings:

FIG. 1 shows a model of the tip-sample gap.

FIG. 2 shows a first embodiment of a deflection sensor in accordance with the invention.

FIG. 2B shows a device for ESR measurements including a second embodiment of the invention.

FIGs. 3 A, B show further variants of the deflection sensor according to the invention.

FIGs. 4 A, B , C illustrate the use of the invention as instrument for surface investigation with different embodiments.

FIGs. 5 A, B illustrate experimental results.

FIGs. 6 A, B, C illustrate further experimental results.

MODE(S) FOR CARRYING OUT THE INVENTION

Referring now to FIG. 1, a RC parallel circuit 1 is shown as a model to facilitate the understanding of the generation of higher harmonics in the interface or gap separating a cantilever and a second surface. The RC parallel circuit 1 is an electrical model of this gap, to which a DC voltage is applied. The input microwave signal ω as generated in a microwave generator (not shown) is coupled into the gap area, for example via either the tip or the sample holder. The input microwave signal has a frequency ω The radiation emerging from the gap includes components with harmonic frequencies $n\omega$. These components are generated due to non-linearity of the resistance R(V) and/or the capacitance C(V) with respect to the voltage.

Referring now to figure 2A, an example of the basic variant of the invention is shown schematically. A flexible cantilever **220** with a tip at its apex and the sample holder **230** with a sample **231** are connected to a DC voltage source **250**, which provides an bias voltage across the interface. Due to the oscillations of the cantilever, which may either oscillate at its resonant frequency or at the frequency of an externally supplied signal, the gap between the tip and sample is modulated causing the emission of radiation including the fundamental ω and higher harmonic frequencies $n\omega$ signals. These signals are received by an antenna **261** and amplified in a microwave amplifier **260** for further processing (displaying, controlling, etc.). This simple variant of the invention is of particular interest when building large arrays of cantilevers. Every cantilever of an array may be tuned to a different base frequency. A spectrum analyzer is then employed to separate the contribution of each cantilever to the detected signal giving a ready possibility to observe the deflection of each cantilever in the array. The excitation energy necessary to balance the energy dissipation of the cantilever has to be provided in this basic variant externally, e.g. by heating, radiation, and the like. When no external field is supplied, it is desirable to have a high resonant frequency of the cantilever. Cantilevers which resonate at frequencies between 0.01 GHz and 1.0 GHz are known from Binh et al., Surface Science 301 (1994), L224.

Figure 2B depicts means for externally exciting the lever oscillation by electromagnetic radiation **240**. A device for measuring the electron spin resonance (ESR) of a sample is shown, which differs from the one described by Rugar et al. in NATURE 360, 563 (1992), in that the deflection of the cantilever is sensed by the detection of higher harmonics generated in the gap between the cantilever **232** carrying the ESR sample and a second (reference or "piggybacked") plane provided with a metallic tip **222**. The rf coil **240**, the magnet **291**, and the sweep coil **292** are standard parts of an ESR measurement equipment. The modulation of the magnetic field at the sample gives rise to a cantilever vibration amplitude of typically around one nanometer, detected as a variation of the higher harmonic signal. This

signal is generated in the gap between the tip **222** and the silicon cantilever **232**. The signal generator **293** sweeps the magnetic field to bring the spins in resonance with the applied rf frequence, which is half of the resonance frequency of the cantilever. A detection circuit **262** is tuned to higher harmonics of this resonance frequency.

Another variant of the invention is shown in FIG.3A. In this example, the microscope particularly includes a cantilever **320** made of semiconducting material **321** Facing its back plane is a metallic tip **323**, which is connected to a microwave source **340**. A DC voltage is applied to the tip **323** and the cantilever **320**. The voltage can be tuned to a value appropriate for the material of the cantilever. Further clamping means (not shown) are provided to keep the distant between tip and cantilever at a default value of 50 to 100 nm. It is important to notice that this gap width is well above the distance over which tunneling of electrons occurs, i.e. significantly larger than in case of the piggybacked STM described in the patent US-A-4 724 318. The gap width is also large enough to prevent a collision of the tip **323** and the cantilever **320** under normal conditions, hence, it is not necessary to provide the tip with a positioning system controlled by another feedback loop. To run however this variant of the invention in a mode which is commonly known in the field of scanning force microscopy as "constant force mode," an integrating circuit **371** is provided , which controls the positioning means **331** of the sample as part of a feedback loop **370**.

In the described variant further an external microwave signal is fed through the tip **323** to the gap between the tip and the cantilever. The input microwave signal source **340** is connected to the DC voltage circuit by a bias tee **341**. The emitted radiation ω **n**ω is received by the antenna **361**. The amplifying circuit includes a preamplifier **362**, with a bandwidth ranging from 1GHz to 4GHz and an amplification of 40 dB, a band-pass filter **363** (2.1-3.5 GHz) for eliminating noise and unsought frequency components from the signal. The following spectrum analyzer **364** produces a frequency

resolved display of the signal. The output of the spectrum analyzer can alternatively be used as input to the integrating circuit **371**.

As another aspect of the invention, a unit comprising microwave source, antenna, amplifiers, and feedback circuit can be built attachable to any known atomic force microscope (AFM). The deflection of the AFM cantilever can be detected with an accuracy of approximately 10 picometer without encountering the stability problems which prevented the use of STM-based detection methods in commercial AFMs.

A compact design in accordance with the invention is shown in FIG. 3B, where the additional metallic tip is replaced by a metallic coating **322** of the cantilever **320**. Further, the output of the spectrum analyzer **364** is connected to the input of a phase locked loop (PLL) **372** controller which forms part of two feedback loops **370, 350**, the first of which is locked to the resonant frequency of the cantilever. This loop, which comprises a summer **374**, is used to electrostatically excite the oscillation of the cantilever **320**. As the PLL is responsive to frequency shifts in the signal, the shown device can be employed to measure the damping of the cantilevers oscillation. A constant damping mode can be achieved by connecting the rms (root mean square) output of the PLL after further smoothing by an integrator **373** as control signal to the positioning means **331** of the sample holder **330**.

Referring now to FIGs. 4A , 4B, and 4C, variants of a surface inspection tool, e.g. a dopant profiling instrument, according to the invention are shown. The first variant, as depicted by FIG. 4A, an electrostatically excited version of the invention as described above (FIG. 3A), is provided with switching means **474**. When the switch is in position 1, the detection of the higher harmonic is used for deflection control. In position 2 however the microwave source is connected to the gap between the cantilever **420** and the sample holder **430** making a dopant profiling possible. It is also possible to provide a second microwave source with a second base frequency. Using

this particular embodiment it is possible to simultaneously detect the deflection of the cantilever and inspect the surface of a sample.

With respect to the example described above, the dopant profiler of FIGs. 4B and 4C comprises additional means to detect the deflection of the cantilever, said means being based on methods known in principle and partly described above. Examples are shown wherein the deflection of the cantilever is either measured by a piezoresistive method (FIG. 4B) or by a beam deflection apparatus measuring the intensity of a laser beam, reflected by the back of the cantilever (FIG. 4C). However, any other known deflection detection method can be applied instead.

In both embodiments the metal coating **422** of the cantilever **420** is connected to a current/voltage converter **490** to operate the cantilever in an STM mode. A switch **476** now is provided with the feedback circuit **470** which allows to choose automatically between different input signals. The switch can be either programmed or controlled by an external device, if for example the topology of the sample is accurately known, which is the case in IC manufacturing. As an alternative, the deflection is monitored with at least a second defection detection method, parallel to the one which currently supplies the input signal to the feedback circuit **470**. In the latter case the switch **476** automatically alters its position when the currently applied signal deviates significantly from its expected values.

Both variants as shown in FIGs. 4B and 4C differ in the way, in which the radiation emanating from the gap area is received: The embodiment of FIG. 4A includes a tunable cavity **465** as described for example by Michel et al., allowing a preselection of the signal frequency and a very sensitive detection of the signal. very sensitive detection of radiation with a narrow bandwidth. In this embodiment the use of a deflection measurement method is preferred which does not interfere with the properties of the cavity as a resonator. Therefore, a piezoresistive layer **423** is incorporated into the cantilever body **420**. The piezoresistive element is part of mainly a

Wheatstone bridge arrangement 480 to measure its resistance and therewith derive the deflection of the cantilever 420. The piezoresistive layer can be replaced by piezoelectric elements, which produce a voltage in sympathy with the bending of the cantilever.

In the embodiment of FIG. 4C, no cavity is used and the antenna is formed by the conductive coating 422 of the cantilever. Input and output paths of the high frequency signal are separated from the DC circuit 450 by bias-tee elements 441, 466. As said above, the absence of a cavity allows to use a broader variety of deflection measuring methods. In the shown embodiment the intensity of a reflected laser beam 482 is measured, whereby this intensity depends on the bending of the cantilever 420.

It is seen as an obvious task for a skilled person to combine different elements of the aforedescribed embodiments, in particular to select a specific way of coupling the input signal to the gap and coupling the output signal to the amplifier cascade, to replace the conductive coating of the cantilever by a cantilever made of conductive base material, or to replace the coating by a piggybacked tip as shown in FIG. 3A.

As said above, the new microscope in accordance with the invention is advantageously used to characterize the surface of integrated circuits (IC). Figures 5 shows results obtained by investigating an n-type silicon sample doped with boron ions. Figure 5A depicts the sample structure consisting of alternating stripes of an and p+ doped silicon. Each stripe has a width of approximately ten μm. Such a grating can be found in a similar form as source/channel/drain area of the PMOS device. In FIG. 5B the intensity of the second harmonic signal is shown as a function of the bias voltage and the position of the tip along a line running perpendicularly to the n and p+ doped stripes. The line-scans are taken at -1.45 V (a) , -0.55 V (b) , and 1.2 V (c), respectively. For reasons of clarity, the origins of the curves are shifted and curve b is enlarged by a factor of 5. Using these scans regions having a high concentration of dopants can be distinguished from regions

with a low concentration, or from depletion zones. Figures 6 shows similar results gained by investigating a sample doped with arsenic (n+). The lines-scans, taken with a bias voltage of 1.15 V (a), -1.15 V (b), and -1.50 V (c), respectively, clearly show the lateral dopant profile. The peak amplitude is much larger in the low-doped regions than it is in the high-doped regions. The resolution found lies below 35 nm. The resolution can be enhanced by controlling the humidity within the microscope. A simultaneously recorded line-scan (d) shows the physical height of the sample as measured in the STM and AFM operation mode of the microscope. The measurement is also depicted in a three-dimensional plot (FIG. 6C) with the horizontal axes being the bias voltage in volts and the position in nanometer, respectively. The vertical axis gives the second harmonic signal in nanoVolts (nV).

CLAIMS

1. An apparatus for measuring a force exerted upon or a deflection of a flexible cantilever (220, 320, 420), especially of an Atomic Force Microscopy (AFM) cantilever, comprising antenna means (261, 263 , 361, 461), amplifying means (260, 262, 362-364, 462-464), and means (250, 350, 450) to apply in operation a DC voltage to said cantilever.

2. The apparatus in accordance with claim 1, wherein the amplifying means (260, 262, 362-364, 462-464) are designed to detect a higher harmonic ($n\omega$) of a high frequency signal (ω).

3. The apparatus in accordance with claim 1, wherein the amplifying means (260, 262, 362-364, 462-464) are designed to operate in a frequency range of 10 MHz to 100 GHz.

4. The apparatus in accordance with claim 1, wherein either the cantilever (220, 320, 420), sample holding means (230, 330, 430), or a reference plane or tip (323, 423) form a part of the antenna means.

5. The apparatus in accordance with claim 1, further comprising means (240, 340, 341, 440, 441) for exciting oscillations of the cantilever (320, 420).

6. The apparatus in accordance with claim 1, further comprising means (240, 340, 341, 440, 441) for applying a high frequency electrical signal to the gap between the cantilever and a sample, or to the gap between the cantilever and a reference plane or tip (323, 423).

7. The apparatus in accordance with claim 1 , further comprising a cavity (465) with conductive walls enclosing the cantilever (420), preferably with one of said walls being moveable relatively to the others.

8. The apparatus in accordance with claim 1 , wherein the cantilever comprises electrically conductive material (322, 422).

9. The apparatus in accordance with claim 1, preferably to be used as dopant profiler, further comprising magnetic or piezoelectric actuator means for controlling the distance between cantilever (320) and the surface of a sample (331), force detection means (480, 482) for measuring the deflection of the cantilever, and switchable feedback means (470, 475, 476) for controlling said actuator means, said feedback means being switchable to said force detection or to the output of the amplifying means.

10. The apparatus in accordance with claim 1, preferably to be used as dopant profiler, further comprising magnetic or piezoelectric actuator means for controlling the distance between cantilever (320) and the surface of a sample (331), means (490) for detecting a tunnel current between tip and sample, force detection means (480, 482) for measuring the deflection of the cantilever, and switchable feedback means (470, 475, 476) for controlling said actuator means, said feedback means being switchable to said tunnel current, to said force detection, or to the output of the amplifying means.

11. Sample analyzing apparatus, comprising an apparatus in accordance with claim 1, means for positioning a sample (330) means for processing measured force or deflection signals to generate a screen display , and means for permanently storing the processed force or deflection signals on a magnetic medium.

12. A method for measuring a force exerted upon or a deflection of a flexible cantilever (220, 320, 420), especially of an Atomic Force Microscopy (AFM) cantilever, comprising steps of generating a high frequency radiation in a gap between said cantilever and a second

surface (230, 231, 323, 330, 423), receiving and amplifying said radiation and determining frequency shifts and/or amplitude shifts thereof.

13. The method in accordance with claim 12, wherein oscillations of the flexible cantilever (220, 320, 420) are excited by an externally applied force.

14. The method in accordance with claim 13, wherein oscillations of the flexible cantilever (220, 320, 420) are excited by an externally applied electrical signal.

15. The method in accordance with claim 12, applied for investigating surface and/or volume properties of a sample (231, 331).

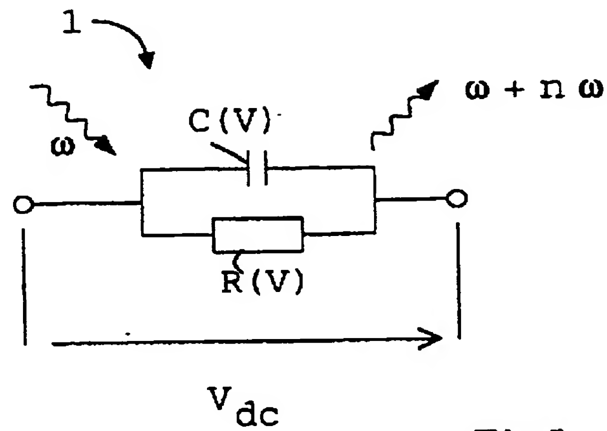

Fig.1

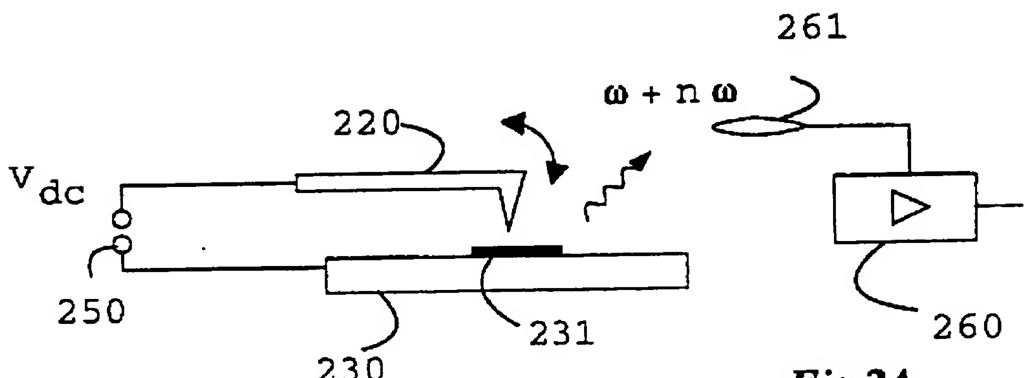

Fig.2A

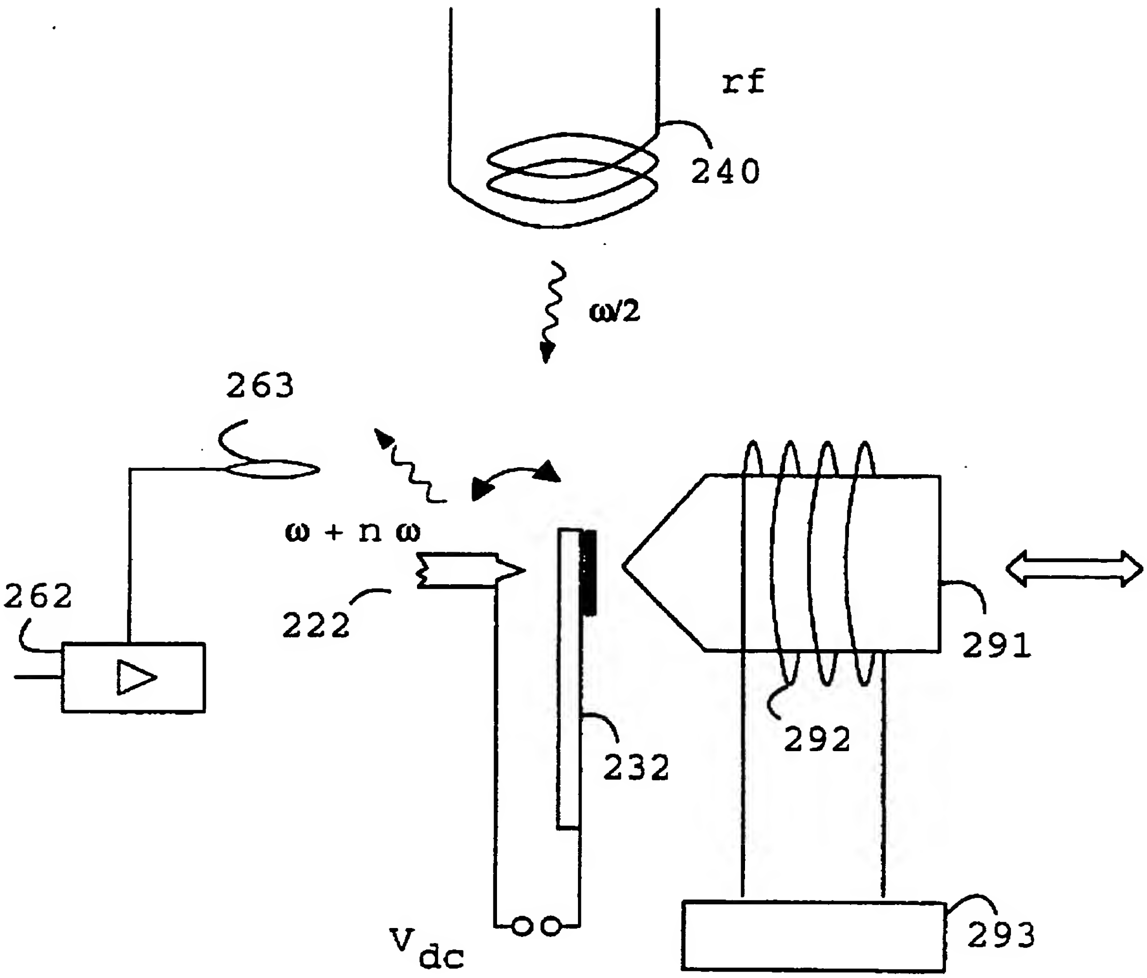

Fig.2B

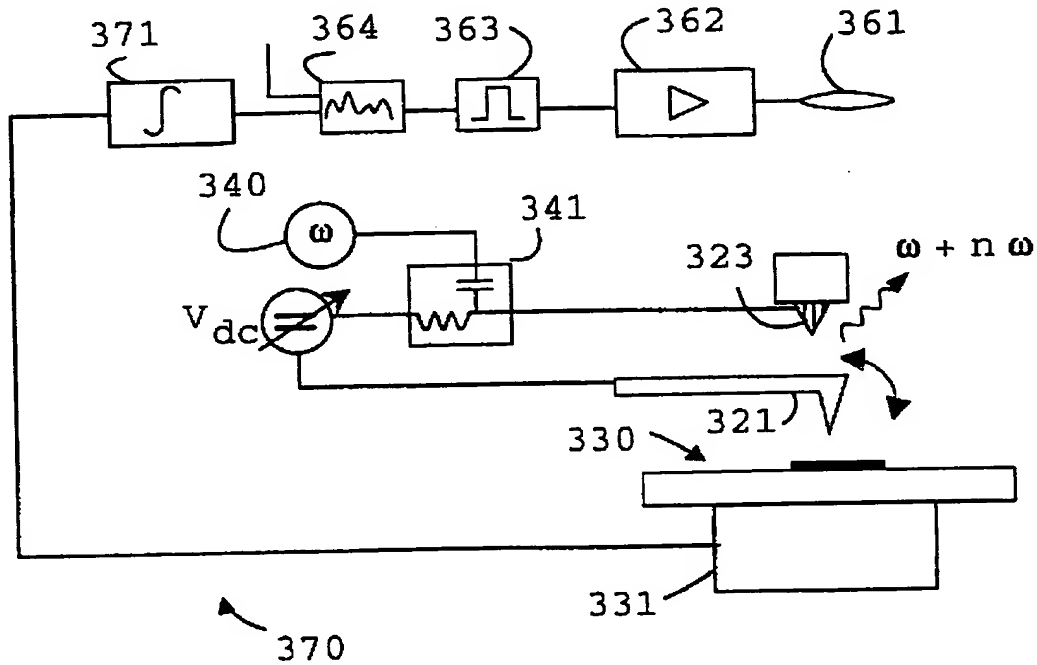
371
364
363
362
361
340
ω
341
323
ω + n ω
V_{dc}
321
330
331
370

Fig.3A

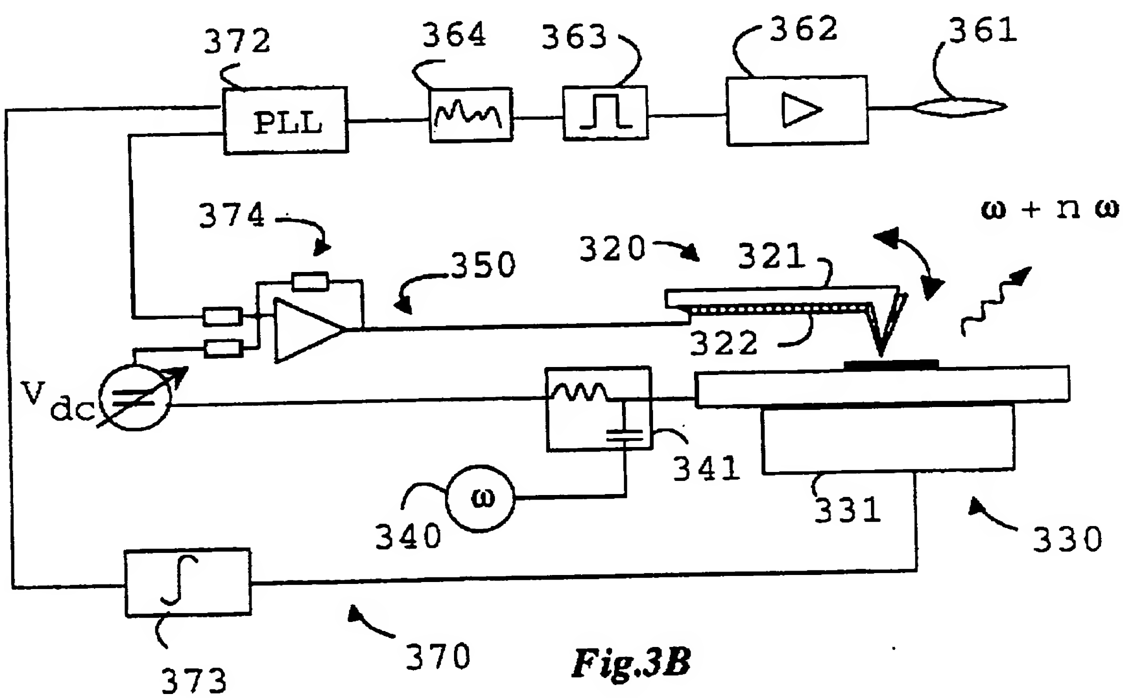
372
364
363
362
361
PLL
374
350
320
321
ω + n ω
322
V_{dc}
341
ω
340
331
330
373
370

Fig.3B

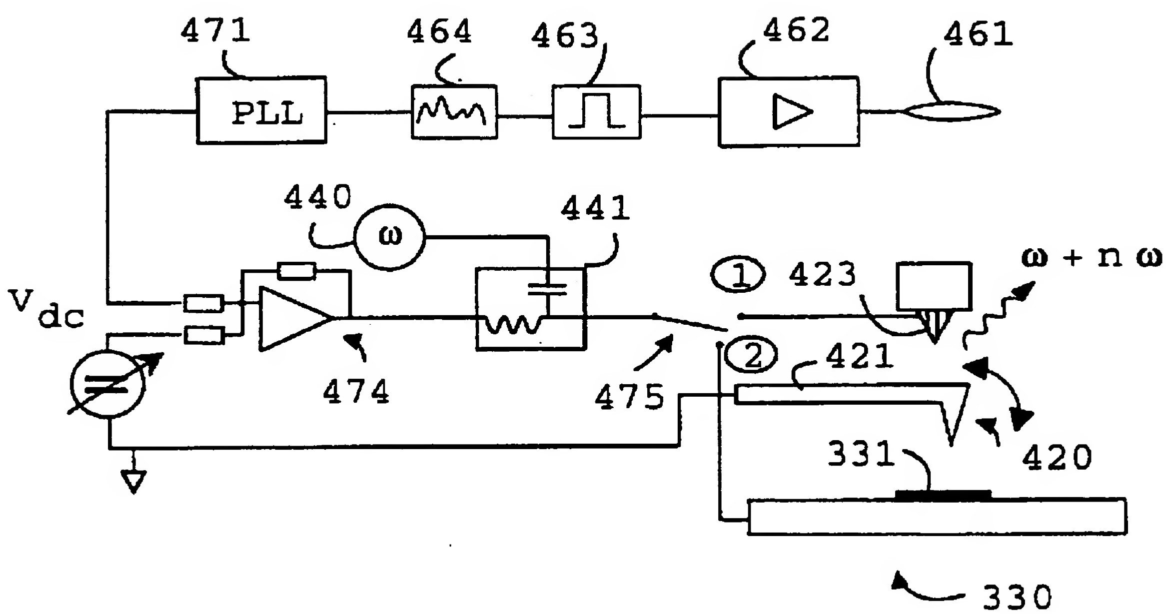
471
464
463
462
461
PLL
440
ω
441
V_{dc}
1
423
ω + n ω
2
421
474
475
420
331
330

Fig.4A

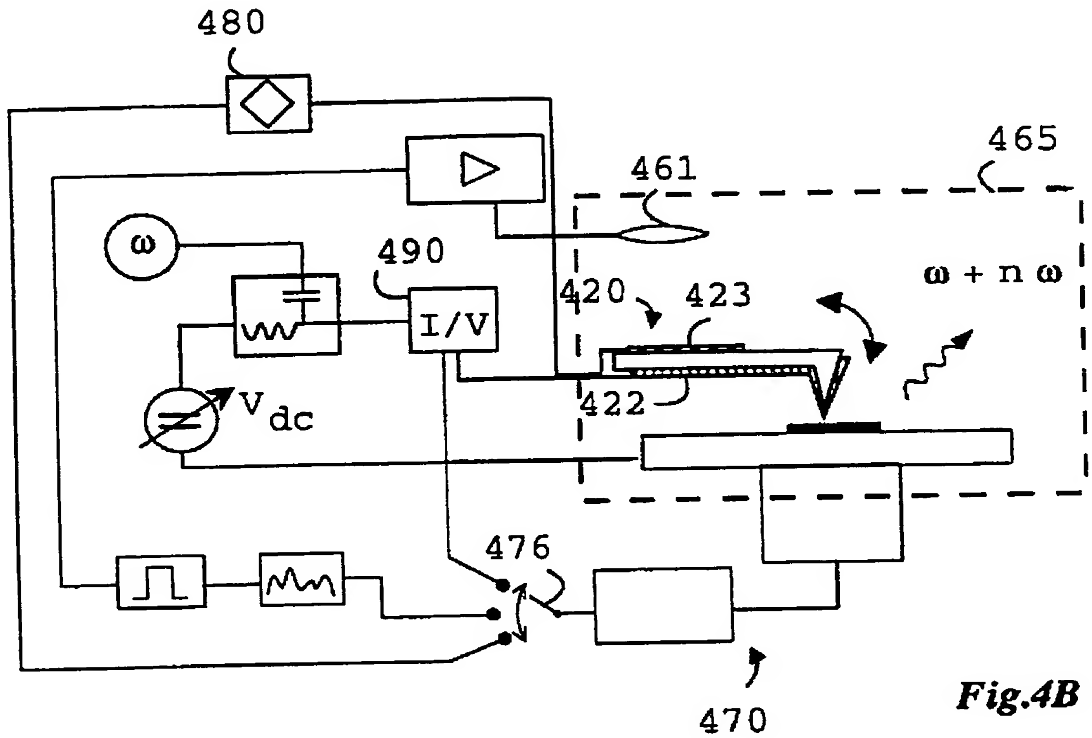
480
465
461
ω
490
I/V
420
423
ω + n ω
V_{dc}
422
476
470

Fig.4B

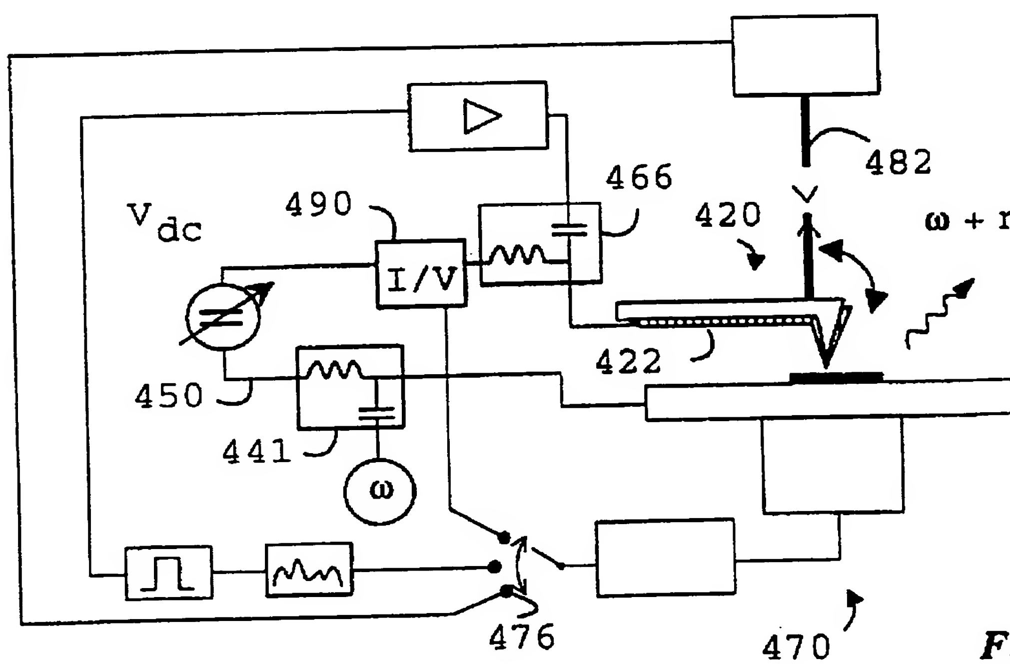
482
466
490
V_{dc}
420
ω + n ω
I/V
422
450
441
ω
476
470

Fig. 4C

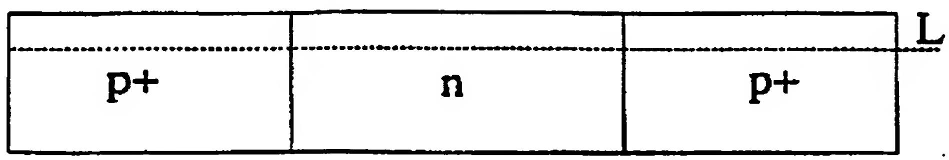

Fig.5A

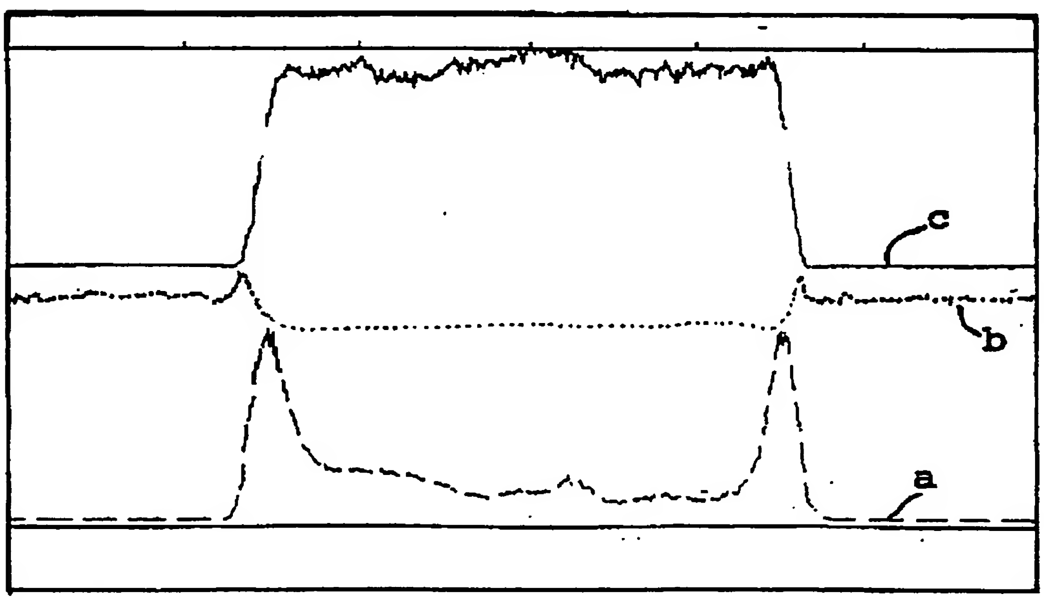

Fig.5B

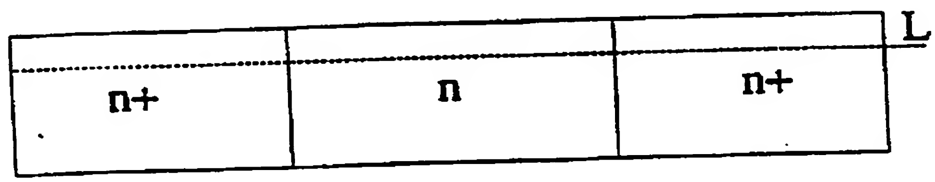
L
n+
n
n+

Fig.6A

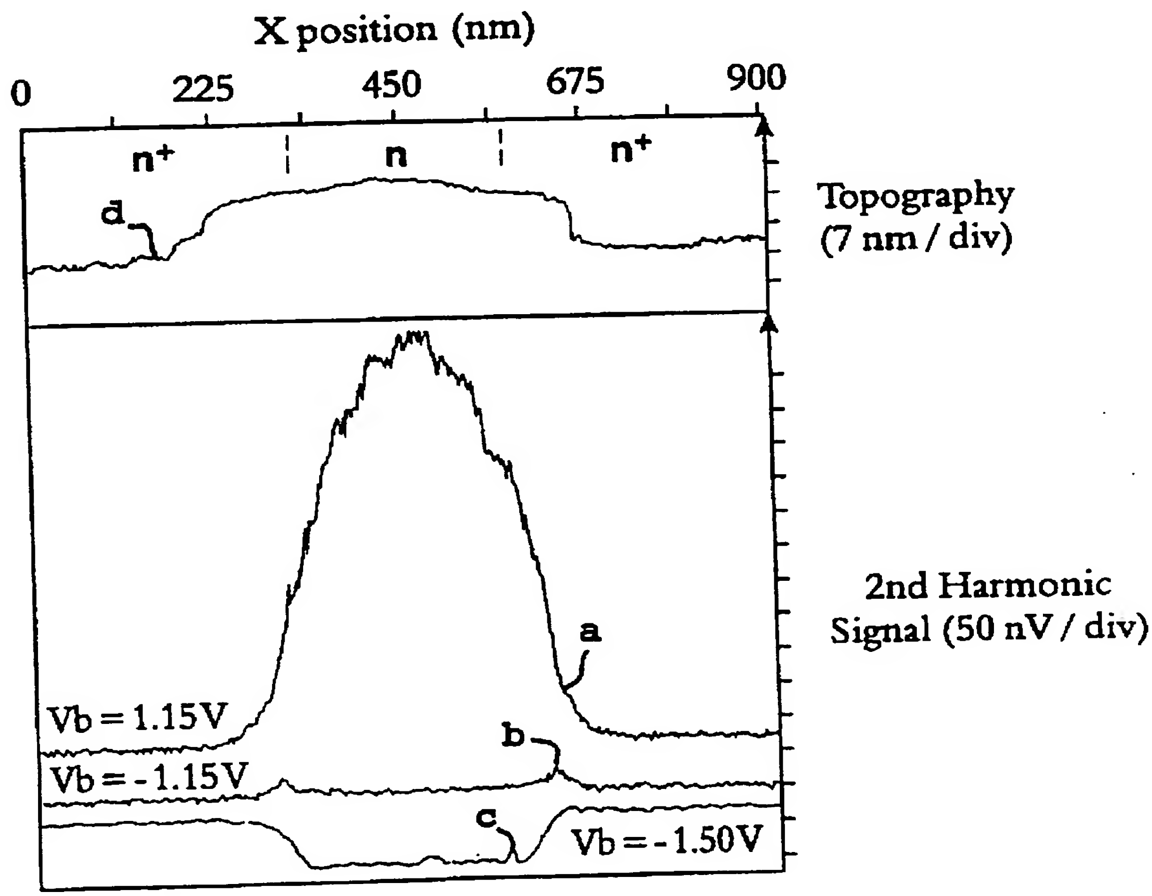
X position (nm)
0
225
450
675
900
n+
n
n+
d
Topography
(7 nm / div)
2nd Harmonic
Signal (50 nV / div)
a
Vb = 1.15V
b
Vb = -1.15V
c
Vb = -1.50V

Fig.6B

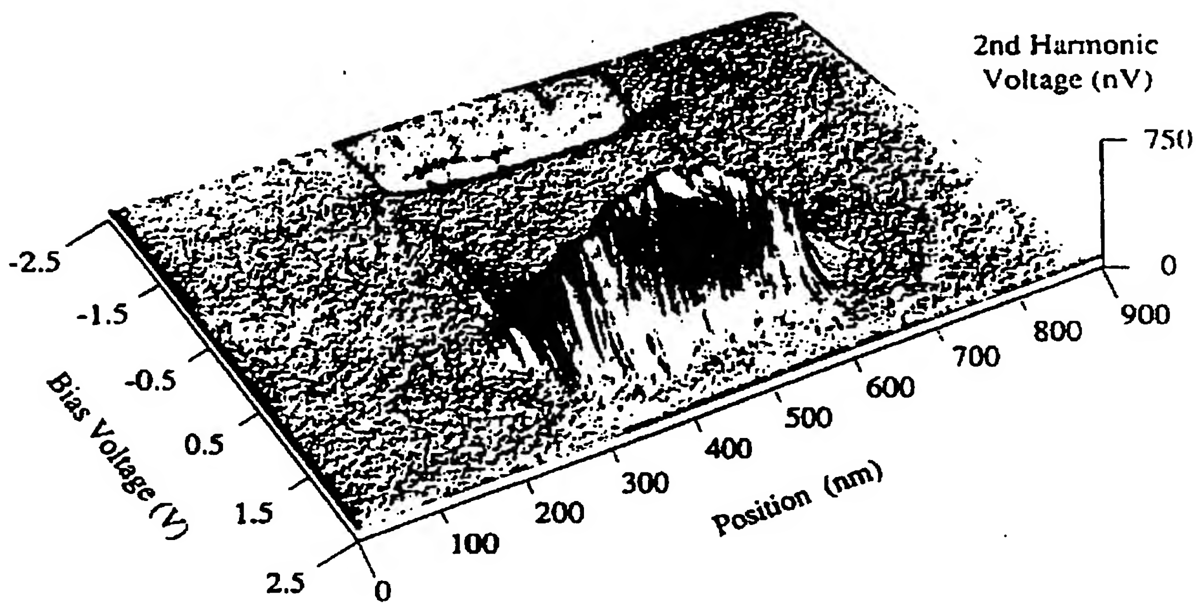
2nd Harmonic
Voltage (nV)
750
0
-2.5
-1.5
-0.5
0.5
1.5
2.5
Bias Voltage (V)
0
100
200
300
400
500
600
700
800
900
Position (nm)

Fig.6C

INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP 95/00431

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G01B7/34

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G01B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	ELECTRONICS LETTERS, 3 DEC. 1992, UK, vol. 28, no. 25, ISSN 0013-5194, pages 2302-2303, HOU A S ET AL 'Picosecond electrical sampling using a scanning force microscope' see the whole document	1-6,8, 11-15
Y	PHYSICAL REVIEW B (CONDENSED MATTER), 15 MAY 1990, USA, vol. 41, no. 14, ISSN 0163-1829, pages 10229-10232, KRIEGER W ET AL 'Generation of microwave radiation in the tunneling junction of a scanning tunneling microscope' see the whole document	1-6,8, 11-15

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"&" document member of the same patent family

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Date of the actual completion of the international search	Date of mailing of the international search report
6 November 1995	20.11.95

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Brock, T

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
E	EP,A,0 648 999 (HITACHI LTD) 19 April 1995 see column 3, line 20 - column 5, line 33; figure 1 see column 8, line 5 - column 9, line 58; figure 6 ---	1,3-7, 11-15
A	APPLIED PHYSICS LETTERS, 17 OCT. 1994, USA, vol. 65, no. 16, ISSN 0003-6951, pages 2045-2047, BOURGOIN J -P ET AL 'Semiconductor characterization with the scanning surface harmonic microscope' ---	1-4,6, 9-12,15
A	MICRO- AND NANOENGINEERING 94. INTERNATIONAL CONFERENCE ON MICRO- AND NANOFABRICATION, DAVOS, SWITZERLAND, 26-29 SEPT. 1994, vol. 27, no. 1-4, ISSN 0167-9317, MICROELECTRONIC ENGINEERING, FEB. 1995, NETHERLANDS, pages 539-542, JOHNSON M B ET AL 'Doping profiling with scanning surface harmonic microscopy' cited in the application ---	1-4,6, 9-12,15
A	IBM TECHNICAL DISCLOSURE BULLETIN, vol. 36, no. 10, 10 October 1993 NEW YORK US, pages 571-572, 'Improved method for dopant profiling by force microscopy' see the whole document ---	1,9,10, 15
A	REVIEW OF SCIENTIFIC INSTRUMENTS, vol. 63, no. 9, 1 September 1992 pages 4080-4085, XP 000311662 MICHEL B ET AL 'SCANNING SURFACE HARMONIC MICROSCOPY: SCANNING PROBE MICROSCOPY BASED ON MICROWAVE FIELD-INDUCED HARMONIC GENERATION' cited in the application ---	1-4,6,7, 11,12,15
A	10 YEARS OF STM. 6TH INTERNATIONAL CONFERENCE ON SCANNING TUNNELING MICROSCOPY, INTERLAKEN, SWITZERLAND, 12-16 AUG. 1991, vol. 42-44, pt.A, ISSN 0304-3991, ULTRAMICROSCOPY, JULY 1992, NETHERLANDS, pages 379-387, SEIFERT W ET AL 'Scanning tunneling microscopy at microwave frequencies' cited in the application --- -/--	1-4,6,7, 11,12,15

1

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	REVIEW OF SCIENTIFIC INSTRUMENTS, APRIL 1994, USA, vol. 65, no. 4, pt.1, ISSN 0034-6748, pages 918-921, STRANICK S J ET AL 'A tunable microwave frequency alternating current scanning tunneling microscope' ---	1,2,4,6, 11,12,15
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A	APPLIED PHYSICS LETTERS, vol. 63, no. 18, 1 November 1993 pages 2496-2498, XP 000408694 ZUGER O ET AL 'FIRST IMAGES FROM A MAGNETIC RESONANCE FORCE MICROSCOPE' -----	1-3, 11-15

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/EP 95/00431

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP-A-0648999	19-04-95	JP-A- 7167868	04-07-95
US-A-5267471	07-12-93	JP-A- 6026855	04-02-94

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